Evaluation of 10 Methods for Initializing a Land Surface Model

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ABSTRACT

Improper initialization of numerical models can cause spurious trends in the output, inviting erroneous interpretations of the earth system processes that one wishes to study. In particular, soil moisture memory is considerable, so that accurate initialization of this variable in land surface models (LSMs) is critical. The most commonly employed method for initializing an LSM is to spin up by looping through a single year repeatedly until a predefined equilibrium is achieved. The downside to this technique, when applied to continental- to global-scale simulations, is that regional annual anomalies in the meteorological forcing accumulate as artificial anomalies in the land surface states, including soil moisture. Nine alternative approaches were tested and compared using the Mosaic LSM and 15 yr of global meteorological forcing. Results indicate that the most efficient way to initialize an LSM, if possible and given that multiple years of preceding forcing are not available, is to use climatological average states from the same model for the precise time of year of initialization. Three other approaches were also determined to be preferable to the single-year spinup method. In addition, low-resolution spinup scenarios were devised and tested, and based on the results, an effective yet computationally economical technique is proposed.

1. Introduction

Land surface models (LSMs) simulate the physical processes that partition precipitation and solar radiation after they reach the ground. LSMs enable spatially and temporally continuous and physically consistent estimates of soil moisture, surface temperature, evapotranspiration, and other terrestrial stocks and fluxes of water and energy to be produced in an economical manner. Thus LSMs are valuable tools for studying the water and energy cycles and are important components of weather and climate prediction systems.

In addition to the shortcomings inherent to any parsimonious numerical representation of highly variable and nonlinear physical processes, the fidelity of LSM simulations is limited by the accuracy of the input fields (static parameters and meteorological forcing) and initial conditions. Initial conditions for a land surface model are the spatially varying set of fields that describe the surface water and energy states at the instant a simulation begins. These may include the water content and temperature of each soil layer, the depth, heat content, density, and liquid water storage of the snowpack, canopy water content, and other properties of the vegetation. All else being the same, "perfect" initial conditions actually vary among LSMs because the climatology of each model is determined largely by its physics (e.g., Koster and Milly 1997). The input forcing data and vegetation, soil, and topographical parameters can affect LSM climatology as well. Because model climatologies tend to differ from those observed in nature, perfect initial conditions are not necessarily a faithful depiction of the earth. Instead, they are the set of states that would result from a long-term simulation of a stable LSM with a consistent forcing dataset. Flawed initial conditions may produce fallacious trends as the state variables drift back toward the modeled ideal, potentially leading to inaccurate assessments of interannual- to climate-scale variations. Hence careful attention to the initialization procedure is critical in any model-based study.

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Long-term, consistent forcing datasets are rarely available for spinning up a land surface model toward perfect initial conditions. Furthermore, multiyear simulations can be computationally expensive, depending on the spatial resolution and coverage. So modelers resort to other methods for spinning up or otherwise initializing their LSMs. Perhaps the most common method is to loop repeatedly through a single year. When the land surface states and/or fluxes equilibrate (cease to vary appreciably from year to year), the spinup is considered complete and the experimental simulation is allowed to commence. For example, the 10 groups that participated in the Global Soil Wetness Project (Dirmeyer et al. 1999) spun up their land surface models by looping through integrations with 1987 forcing data for 2 to 10 repetitions.

Spinup time was defined in the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) Phase 1 as the number of yearly integrations necessary to yield changes in annual mean latent and sensible heat fluxes that were less than 0.1 W m^{-2}. Based on this definition, Yang and Dickinson (1995) found that the spinup times for 22 PILPS phase 1 LSMs running on a single point and starting from a middling moisture condition ranged from 2 to 10 yr for a tropical forest and from 2 to 15 yr for a midlatitude grassland site. Adding the constraint that root zone soil moisture must not change more than 0.1 mm and starting from saturation, Chen et al. (1997) found that the spinup times for 23 PILPS phase 2 models varied from 1 to 60 yr for a grassland site in the Netherlands. Others have defined spinup time based on *e*-folding time (Delworth and Manabe 1988) or halving time (Simmonds and Lynch 1992). The downside to the single-year loop technique is that 1 yr cannot provide an accurate climatology, and any regional meteorological anomalies will accumulate as anomalies in the land surface states until an unnatural equilibrium is achieved (Schlosser et al. 2000). Spinup time also varies depending on the conditions prescribed at the outset. Cosgrove et al. (2003) compared three initialization techniques, a wet initialization, a dry initialization, and initialization by output from the National Centers for Environmental Prediction and Department of Energy Global Reanalysis 2 (NCEP/DOE R-2; Kanamitsu et al. 2002). They found that the last produced a substantial reduction in spinup time for all four LSMs in the study despite the differences between the NCEP/DOE R2 climatology and those of the LSMs. Walker and Houser (2001) demonstrated that spinup time could be reduced through the assimilation of observation-based surface soil moisture data; however that technique was not evaluated here.

The following sections describe and assess 10 initialization and spinup methods and one hybrid of two promising methods. The experiments were motivated by a desire to initialize LSMs in a way that would minimize the adverse effects of imperfect initial conditions given a shortage or complete lack of background forcing, also taking into account that computer processing time may be limited. Mosaic was the LSM used in the experiments (save for two in which Noah LSM states were used to initialize Mosaic); however, the relative outcomes are expected to be essentially model independent. Soil moisture was the only state variable examined here, which simplified the comparisons. Soil temperature has less variational inertia than soil moisture and also less interannual variability, so that it reaches equilibrium during spinup in much less time than root zone or total column soil moisture (Houser et al. 1999; Cosgrove et al. 2003). Initialization of snow water equivalent, which has no upper bound, is beyond the scope of this work.

2. Background

a. Mosaic

Mosaic (Koster and Suarez 1992) is a well established and theoretically sound LSM with roots in the Simple Biosphere model of Sellers et al. (1986). The primary innovation of Mosaic was its treatment of subgrid-scale variability. It divides each model grid cell into a mosaic of tiles (after Avissar and Pielke 1989) based on the distribution of vegetation types within the cell. Each tile represents one vegetation class and is weighted by the cell fraction of vegetation in that class. Tiles are modeled as independent soil columns, and therefore do not interact with each other directly. The version of Mosaic used in this study includes three soil layers (0–2, 2–150, and 150–350 cm) and a single-layer snow formulation. Modeling experiments for which the total soil column depth is shallower are likely to spin up more quickly than Mosaic did in this study, but soil depth should not influence the relative effectiveness of the initialization techniques tested here. Surface flux calculations in Mosaic are similar to those described by Sellers et al. (1986). The state fields that were carried from one simulation to the next or otherwise initialized were water in each soil layer, snow water equivalent, canopy interception and humidity, and surface and deep soil temperatures.

b. Noah

Since 1993, as a core project within the Global Energy Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP), NCEP has spearheaded a continuing collaboration of investigators from both public and private institutions to develop a modern LSM to be used for operations and research at NCEP and distributed for community usage. The Noah LSM (Chen et al. 1996; Koren et al. 1999) was borne of that effort. Noah has been coupled to NCEP weather and climate prediction models since 1996, and it continues to benefit from a steady progression of improvements (Betts et al. 1997; Ek et al. 2003).

c. GLDAS

The Global Land Data Assimilation System (GLDAS) was developed jointly by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), with the goal of integrating satellite- and ground-based observational data products through forcing, assimilation, and validation, in order to generate optimal fields of land surface states and fluxes (Rodell et al. 2004). GLDAS drives multiple, uncoupled LSMs, including Mosaic and Noah, globally at various resolutions, producing both retrospective and near–real time output. GLDAS has incorporated the Mosaic subgrid tiling approach into its main driver, with a 1-km global vegetation dataset as its basis. Soil and elevation parameters are based on high-resolution global datasets. Multiple options for forcing, parameterizing, and constraining the LSMs are available.

d. Bias-corrected ECMWF reanalysis forcing data

The hydrometeorological forcing dataset used in this study was generated on 0.5° grid with a 6-hourly temporal resolution for 1979–93 (Berg et al. 2005, manuscript submitted to *Int. J. Remote Sens.*). It is largely based on the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-yr Re-Analysis (ERA-15) dataset (Gibson et al. 1997); however biases in the precipitation, air, dewpoint temperature, and the short- and longwave radiation fields were reduced through adjustment of the reanalysis monthly means to those of monthly observation-based fields. Berg et al. (2003) demonstrate the importance of the bias removal for improved hydrologic simulations over the Mississippi River basin.

3. Methods

Thirteen LSM simulations were performed whose specifications were identical except for the manner in which they were initialized. The period of the simulations spanned 2100 UTC 1 January 1987 to 1800 UTC 31 December 1993. All land surface state fields were initialized by the techniques described below. However, in comparing the results, only the total column soil moisture was considered; the effects of initialization on soil temperature, snow depth, and other state variables was not evaluated. To assess the efficacy of each initialization technique, a long-term simulation was needed to produce near-perfect initial conditions at the start of the experimental period, and thus near-perfect output (within the limitations of the LSM). To generate this "truth" output, a run was initialized with the soil water content in all three layers set to 30% of saturation, spun up with forcing from 1979 for 45 consecutive iterations, and then allowed to run through seven additional years (1980–86) to the start of the experimental period (see Table 1). The results of that simulation as it continued into the experimental period were the standard against which all other simulations were compared. All simulations were forced by bias-corrected ECMWF reanalysis data (Berg et al. 2003).

TABLE 1. Specifications of the "truth" simulation.

LSM	Mosaic
Spatial resolution	2° × 2.5°
Subgrid variability	10% cutoff vegetation tiling
Model time step	15 min
Time period	1979–93
Forcing source	Bias-corrected ECMWF reanalysis
Initialization	45 loops through 1979
Soil layers	0–2, 2–150, 150–350 cm

Experimental designs were motivated by several questions. When only a short period of forcing data are available or computer processing time is precious, a modeler may be compelled to begin a simulation with spatially homogenous initial states. Regarding soil moisture, are wet, dry, or average conditions best? Experiments A–C address this question. If more than 1 yr of forcing is available, how best to spin up (experiments D, E, and I)? Are mean states for the given time of year appropriate for initialization, or does interannual variability preclude their usefulness (experiment F)? Using results from another model that is already spun up is an obvious solution, but how important are differences in model climatologies (experiments G and H)? Can we conserve computing resources by spinning up at a lower resolution and still get a good result (experiments J1 and J2)? The experiments are described below and summarized in Table 2.

a. Dry start

Soil water content in all three layers was set equal to 10% of saturation globally. Likewise, soil temperatures were set to 290 K, and all other state fields (i.e., snow water equivalent and canopy water storage) were initialized to zero. This technique would be suitable if the

TABLE 2. Specifications of experimental simulations with key to Figs. 3 and 4.

Key	Initialization technique
A	Dry: soil at 10% saturation
B	Wet: soil at 70% saturation
C	Middling: soil at 30% saturation
D	45 loops through 1987
E	45 loops through mean year of forcing
F	Mean state fields for 2100 UTC 1 Jan
G	Noah output fields
H	Noah output fields scaled to Mosaic
I	7.5 loops through 1987–92
J1	Truth fields degraded to 4° × 5°
J2	Truth fields degraded to 8° × 10°
K1	Mean state fields degraded to 4° × 5°
K2	Mean state fields degraded to 8° × 10°

main factor controlling spinup time was drying of the soil to equilibrium conditions in arid regions.

b. Wet start

Soil water content in all three layers was set equal to 70% of saturation globally. Likewise, soil temperatures were set to 290 K, and all other state fields were initialized to zero. This technique would be suitable if the main factor controlling spinup time was wetting of the soil to equilibrium conditions in moist regions.

c. Middling moisture start

Soil water content in all three layers was set equal to 30% of saturation (a middling value) everywhere. Again, soil temperatures were set to 290 K, and all other state fields were initialized to zero. This is a commonly used method to initialize an LSM when other options are not feasible. This method was used to initialize the spinup simulations for techniques D, E, I, and the truth run as well. These first three homogenous initialization experiments test the hypothesis that a middling initial soil moisture promotes a quicker spinup than a wet or dry initialization.

d. 1987 spinup

This simulation was spun up by forcing the LSM with 1987 data for 45 consecutive iterations. Consequently, our stringent spinup requirement was met: no more than 10 model grid cells experienced a year-to-year change in total column volumetric soil water content that exceeded 0.1%. Because of the prevalence of this spinup technique, it provides the null hypothesis against which the following six alternative techniques are tested. Also, 45 yr is taken as the standard spinup time for subsequent experiments.

e. Climatological spinup

A climatological year of forcing data was created by computing the mean value at each 6-hourly forcing time step based on the 15 yr available. An experimental simulation then was spun up by forcing the LSM with this dataset for 45 consecutive iterations. The hypothesis was that a climatology would produce a better spinup than a real year of data (such as 1986) because annual meteorological anomalies would be removed, thus minimizing the occurrence of abnormally wet or dry land surface conditions (or warm or cold conditions). For example, spinning up with data from 1993, an unusually rainy year in the midwestern United States, would cause the land surface to be extremely wet in that region, which would result in an unrealistic initialization (unless the "perfect" initial conditions happened to be extremely wet as well).

f. Mean state initialization

Climatological land surface state fields for 2100 UTC 1 January were computed by averaging the output from the truth simulation for that precise time of year in 1980–86 and 1988–93, withholding the perfect initial conditions from 1987 (hence the mean of 13 sets of output fields). The model was initialized with these climatological fields. As with the previous experiment, the objective was to reduce the occurrence of unrealistic extremes in the initialization. This method would be useful if a multiple-year simulation had been or could be forced by data from a period other than that leading up to the experimental period, or by a synthetic meteorological dataset (as would result from a long-term climate simulation), or if some other basis for computing a climatology were available.

g. Initialization by a different model

Initializing one LSM with results from another is appealing because model output, such as atmospheric analyses that include a land component, often is available, but the time and computing resources required for spinup often are not. To test the effectiveness of this approach, at least with regard to one particular pair of models, a simulation with the Noah LSM was executed using the same spinup procedure as for the Mosaic "truth" simulation, and with the identical set of subgrid tiles. The 2100 UTC 1 January 1987 land surface state fields from Noah were then used to initialize an experimental Mosaic simulation. The depths of Noah's soil layers were different from those prescribed for Mosaic, and the total depth was only 2 m; hence the wetness and temperature values had to be extrapolated. This was not considered detrimental to the experiment because differences in soil layers between models are common, so that extrapolation is likely to be necessary when employing this type of initialization.

h. Initialization by a different model, scaled

The 14-yr (3-hourly output) mean and standard deviation of each of the land surface states at each grid point was computed for both the Noah simulation described above and the Mosaic "truth" simulation. At each grid cell, the 2100 UTC 1 January 1987 Noah states then were scaled to fit Mosaic using the following equation, and the resulting fields were used to initialize an experimental simulation:

$$M_t = \mu_M + \sigma_M[(N_t - \mu_N)/\sigma_N], \tag{1}$$

where M_t is Mosaic state at time t, μ_M is Mosaic state mean, σ_M is Mosaic state standard deviation, N_t is Noah state at time t, μ_N is Noah state mean, and σ_N is Noah state standard deviation.

i. Subsequent forcing spinup

An experimental simulation was spun up by forcing Mosaic with 1987–92 data repeatedly for 45 yr (7.5 loops through a 6-yr period). Once again, the goal was to minimize the occurrence of anomalously wet or dry land surface conditions (or warm or cold conditions) caused by the meteorological anomalies of a real year used to spin up a simulation. An associated hypothesis tested here was that initializing a simulation with output from the correct day but a different year from a multiyear run is preferable to spinning up repeatedly with the first available year of forcing (the null hypothesis).

j. Low-resolution spinup

The "perfect" initial conditions at 2° × 2.5° resolution were averaged spatially to 4° × 5° resolution on a (subgrid vegetation) tile-by-tile basis. The resulting 4° × 5° states were then applied as initial conditions for the four 2° × 2.5° resolution grid squares within each larger grid square. A similar exercise was performed in which the resolution was degraded to 8° × 10°. The purpose was to simulate the initialization of an LSM with data from the same LSM operating at a lower spatial resolution. This would be useful if the spatial resolution of an intended simulation is high, so that a long-term spinup would be computationally expensive and/or time consuming.

k. Low-resolution, mean state initialization

The mean state fields of option F were degraded to 4° × 5° and 8° × 10° resolutions as in option J. This hybrid method was devised with the goal of combining the economy of a low-resolution spinup with the efficiency of mean state initialization, which, as described in the next section, produced the best results overall.

4. Results

Figure 1 shows the total column soil moisture field and anomaly (departure from the 14-yr mean for that date) for the truth simulation at the start and end of the experimental period. This provides a reference for the errors and anomalies presented in subsequent figures. The errors in the output moisture fields, expressed in percentage volumetric soil water content, for each of the experimental simulations, are plotted in Fig. 2 at four times within the 7 yr, including 3 h after initialization. Note that the errors tend to be very large over Greenland and certain other parts of the Arctic. Because of the lack of an ice sheet model in Mosaic (a common deficiency of LSMs), the simulation of land surface processes in these areas is completely unreliable. In particular, with no ice flow and therefore no mechanism for discharge, snow accumulates indefinitely, shielding soil moisture from the influence of meteorological forcing. Therefore, Greenland and selected other Arctic grid cells were excluded from the calculations of root-mean-square (rms) errors, which are plotted in Fig. 3 at annual intervals. As an alternative means of summarizing the results, the percentage of the land area where the error exceeded 1% volumetric soil

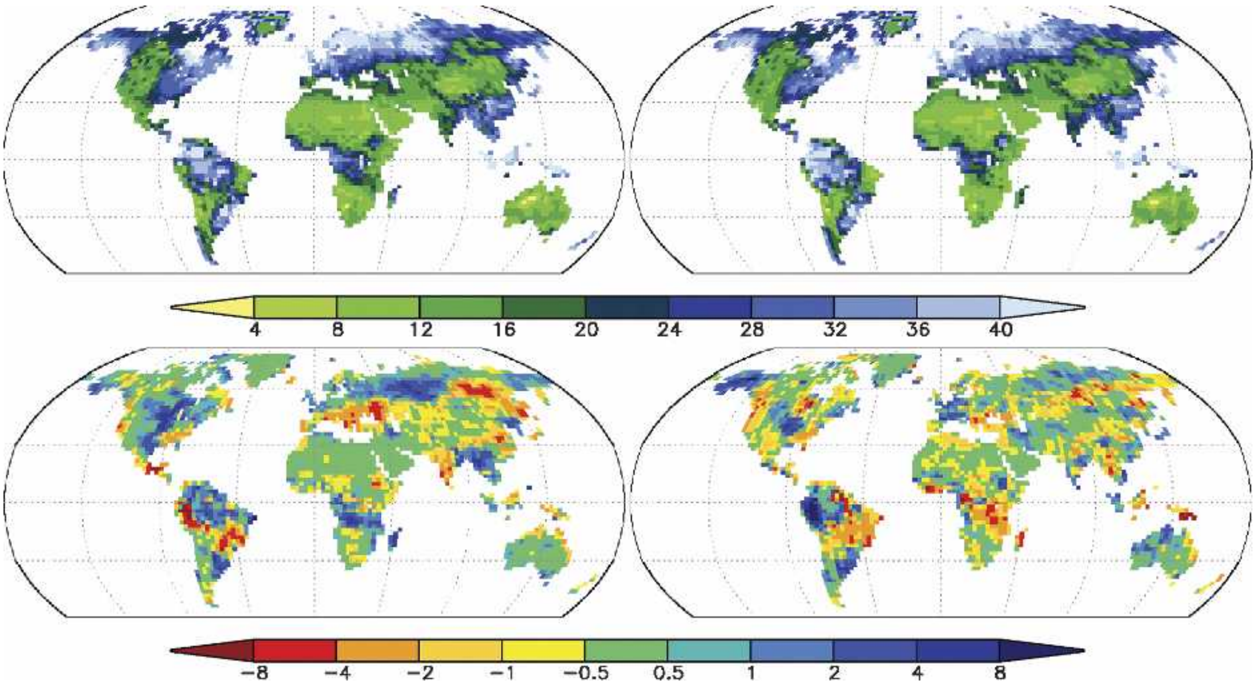

FIG. 1. Volumetric soil water content (%), output from the truth simulation at (top left) 2100 UTC 1 Jan 1987 and (top right) 1800 UTC 31 Dec 1993, and (bottom) corresponding anomalies (difference from 14-yr mean volumetric soil water content for that date and time).

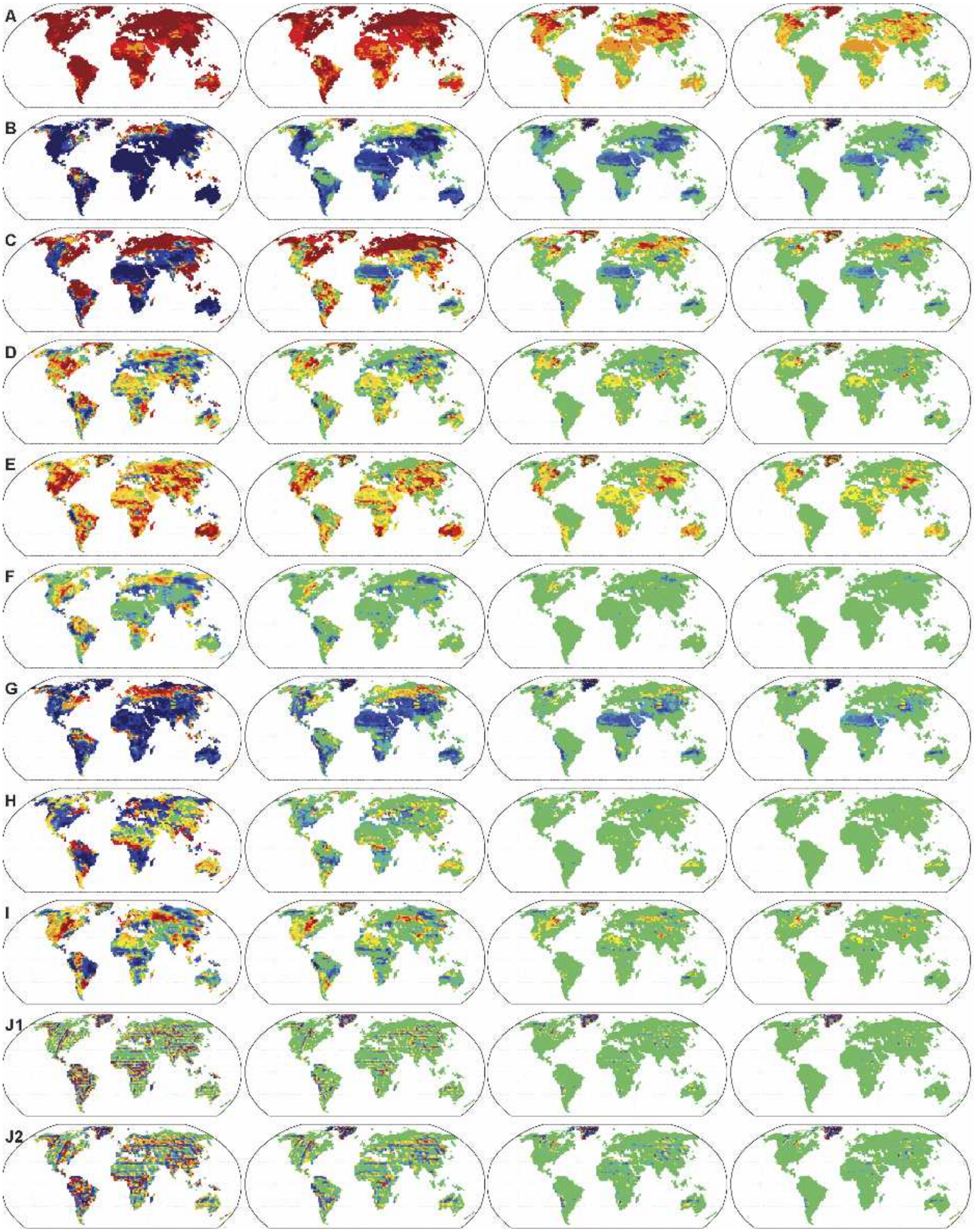

FIG. 2. Difference in output volumetric soil water content fields (%) between experimental simulations (in rows; see Table 2 for key) and truth simulation, for (left to right) 0000 UTC 2 Jan 1987, 2100 UTC 1 Jan 1988, 2100 UTC 1 Jan 1991, and 1800 UTC 31 Dec 1993.

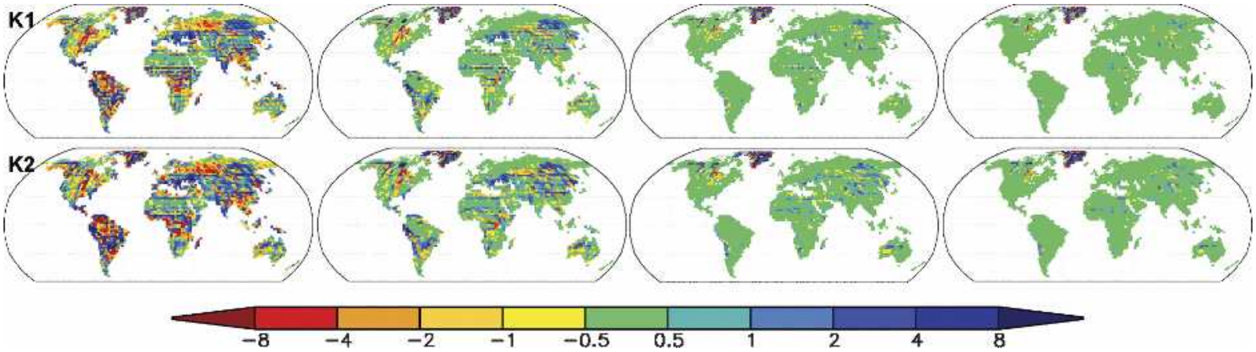

FIG. 2. (*Continued*)

water content, again excluding Greenland, is plotted against time for each experiment in Fig. 4. Below, the techniques are separated into three groups for intercomparison. When not stated, the qualification, "with respect to the Mosaic LSM," is implied in all conclusions about the effectiveness of the techniques.

a. Dry, middling, and wet initializations

A dry initialization (option A) appears to be the worst way to initialize a simulation, as the rms error was still greater than 10% after 1 yr (Fig. 3). Initializing with a uniform 30% saturation (option C) was somewhat better than using a wet value of 70% (option B), though

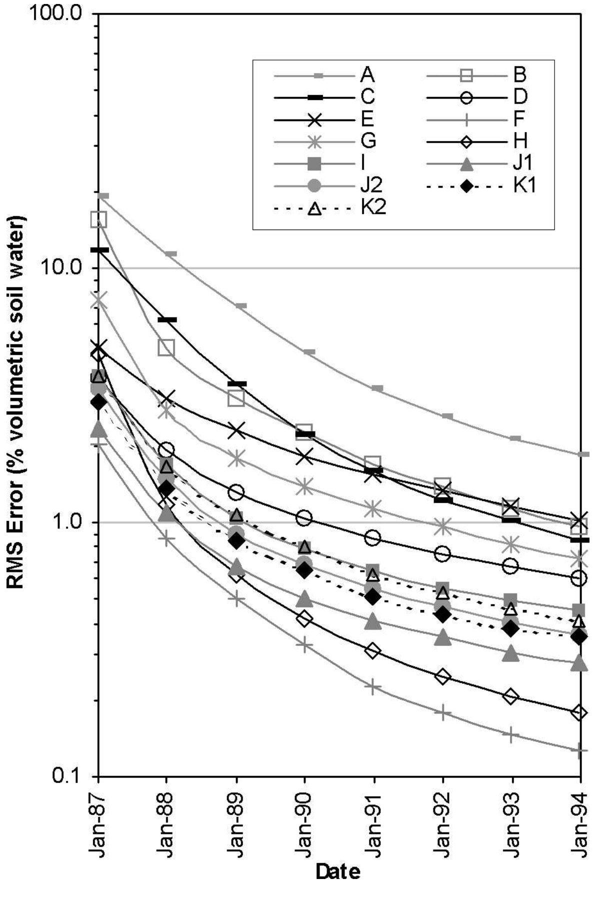

FIG. 3. Rms error (% volumetric soil water) of each of the experimental simulations (see Table 2 for key), plotted 3 h after initialization and every year thereafter. Greenland and permanently ice-covered Arctic grid cells were excluded from the calculations.

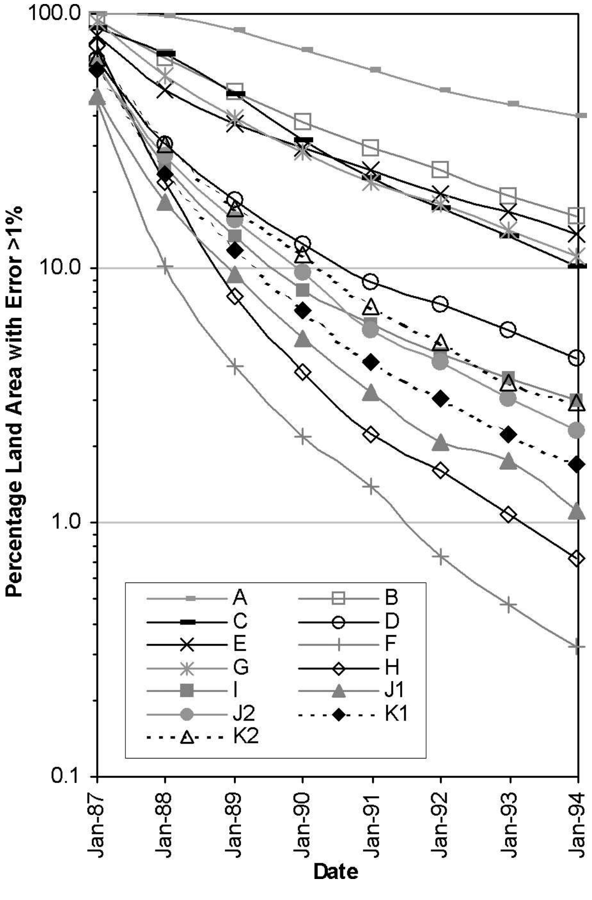

FIG. 4. Percentage of land area where the error was greater than 1% volumetric soil water, for each of the experimental simulations (see Table 2 for key), plotted 3 h after initialization and every year thereafter. Greenland and permanently ice-covered Arctic grid cells were excluded.

not until after the first 3 yr. Hence there was some support for the hypothesis that a middling value is preferable to a wet or dry value. The optimal initial value was not determined, and it surely varies from model to model.

b. 1987 spinup and alternatives

Spinning up repeatedly with a single year of forcing, in this case 1987 (option D), is the standard against which five alternative methods are assessed. These are spinning up with climatological forcing (option E); climatological state initialization (option F); initialization by states from a different LSM, in this case Noah (option G); initialization by Noah states scaled to Mosaic (option H); and spinning up with forcing from several subsequent years (option I). Option D is a reasonable approach whose effectiveness lies in the middle of the 10 techniques described (Figs. 3 and 4). The rms error was 1.94% after 1 yr and 0.60% at the end of the experimental period. Clearly it is preferable to a homogenous state initialization. However, it was only the fourth best option among the six in this group. In particular, the hypothesis that spinning up with multiple years of forcing (option I)—which is similar and often just as practical—is better than using only a single year (option D) appears to be correct. The spinup with 1987–92 forcing (option I) resulted in an rms error that was 0.25% smaller after 1 yr and still 0.15% better on 31 December 1993.

Figure 5 shows the precipitation total and difference from the 1987–93 average for 1987. Comparing this with the soil moisture error for the 1987 spinup simulation on 2 January 1987 (Fig. 2, row D, first column), it can be seen that when spinning up with 1987 forcing repeatedly, the precipitation anomalies for that year accumulate as anomalies in soil water storage, which often translate to errors in the initialization. Among other areas, the initial values are too dry in parts of the southeastern United States, northeastern South America, and southeastern Africa; the initial values are too wet in northwestern South America, Southeast Asia, northwestern Australia, and across much of southern Europe.

Of all the techniques considered here, initializing with climatological state fields (option F) is clearly the most effective. This conclusion is apparent from a quick inspection of the error maps in Fig. 2. From the first day onward this technique resulted in the smallest rms errors (Fig. 3) and the least area where the error exceeded 1% volumetric soil water (Fig. 4). The rms error after 1 yr was 0.87%, a level that was not achieved in the 1987 spinup simulation (option D) until the end of the fourth year.

On the other hand, the climatological forcing spinup (option E) did not cause the land surface to approach a climatological mean wetness state, thus disproving our hypothesis. Rather, it produced an overly dry soil column, and as concluded in the previous section, dry initial conditions are slow to equilibrate. At the start of the experimental period the errors for option E were not particularly large anywhere, and hence the rms errors were comparable to many of the other options. However, Figs. 3 and 4 demonstrate that the results degraded relative to the other options over the next 7 yr. The generation of an overly dry soil column underscores the nonlinearity of hydrological processes. The climatological forcing includes constant, light precipitation and moderate daily insolation, temperatures, and humidity (varying with location and time of year). In the simulation, these conditions promoted excessive evapotranspiration balanced by minimal deep infiltration and runoff, resulting in overly dry soil in the subsurface layers.

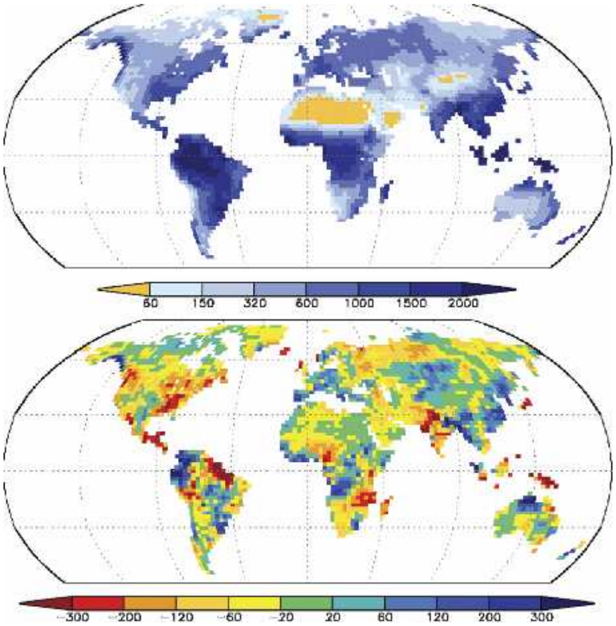

FIG. 5. (top) Total precipitation (mm) for 1987 and (bottom) difference from 1987–93 average annual precipitation.

The suitability of initializing one LSM with fields from another will depend on which two models are involved, particularly the similarity of their climatologies and which tends to be wetter. Chen et al. (1997) found a range of 184 mm in the annual mean root zone (1 m) soil water contents of 23 PILPS Phase 2 LSMs for a grassland site in the Netherlands. At the start of the experimental period the Mosaic global mean 1-m soil water content was 197 mm, while that for Noah was 245 mm, so the difference, 48 mm, was much smaller than the range reported by Chen et al. Directly initializing Mosaic with Noah fields (option G) proved to be reasonable though far from perfect, with an rms error of 2.75% after 1 yr and 0.72% after 7 yr. However, the reverse (initializing Noah with Mosaic fields) may have been worse, since overly wet soil spins up more quickly than overly dry soil. Still, if other options are not available, this technique is likely to be better than a uniform state initialization, which is consistent with the conclusion reached by Cosgrove et al. (2003). Scaling Noah's land surface states to Mosaic (option H) produced very good results, indeed, the second best, with rms errors of 1.17% and 0.18% after 1 and 7 yr.

c. Low-resolution spinup

Initialization of the LSM with "perfect" state fields degraded to lower resolutions was intended to simulate spinning up the model at a low resolution. This technique resulted in a checkerboard pattern of high and low errors (Fig. 2, rows J1 and J2). Rms errors were 1.09% and 1.50% after a year and diminished to 0.28% and 0.36% for the J1 and J2 experiments, which was better than most of the other approaches. As indicated by the difference in errors between the two experiments, the effectiveness of this technique diminishes as the spinup resolution decreases. Effectiveness also depends on the correlation length scales of the forcing data and land surface parameters. Simulations forced and parameterized by data with much variability at the higher spatial resolution will be less efficiently initialized by lower-resolution state fields than those in which the forcing and parameters tend to be more smoothed and homogenous.

To illustrate how a low-resolution spinup could be applied, imagine having 7 yr of forcing data available for spinning up to an experimental period, but limited computing time. One option would be to start from a uniform, middling soil moisture value and spin up at full resolution with the 7 yr of forcing, resulting in an rms error of approximately 0.86% (Fig. 3, option C, 31 December 1993). Alternatively, one could spin up repeatedly with the fourth year of forcing for 48 iterations, at quadruple the length scale, thus using 1⁄16 the computing time and power, or an equivalent of 3 yr at full resolution. Then one would spin up at full resolution with years 5–7 of the forcing, resulting in approximately the same rms as option J2 on 1 January 1990, or 0.68%. Thus, one would have used the equivalent of six model years of computing time at full resolution, rather than seven, and would initialize the experiment with a lower rms error.

Initializing with a climatological mean state field based on a low-resolution spinup simulation (options K1 and K2) may, in some cases, provide an optimal mix of accuracy and economy. Such a field is produced by running a model at low resolution for a sufficient number of years to ensure a reasonable climatology (a 15-yr period proved adequate here), computing the mean field for the start time of year of the experiment, and interpolating the result spatially. Other than the full-resolution mean state initialization (option F) and the two corresponding low-resolution initializations (options J1 and J2), the only approach that produced a better result was the scaled Noah initialization (option H). Rms errors were 3.0% and 3.7% at the start of the experimental period and 0.35% and 0.41% after 7 yr for options K1 and K2.

5. Summary and conclusions

Ten methods for initializing land surface models were evaluated by initializing one 1987–93 Mosaic LSM simulation with each and comparing the output total column soil moisture fields with those from a "truth" run which spanned 1979–93. The most commonly applied method, when a long-term forcing dataset is not available for spinup, is looping repeatedly through a single year until a desired level of equilibrium is achieved. Its disadvantage is that forcing anomalies in the looped year accumulate as artificial anomalies in the initialized land surface states. The desire to identify a more efficient method motivated this study, and the results demonstrate that certain other techniques are superior. In particular, initialization with model-specific mean state fields for the precise time of year proved to be optimal.

Primary nonmeteorological controls on soil moisture spinup time include the soil column depth, hydraulic conductivity (determined by soil type, degree of wetness, and model specific parameters), rooting depth, and the persistence of snow cover. All of these factors regulate the influence of atmospheric forcing on moisture storage. A given weather event (rain or period of dry sun) is more likely to change the soil wetness significantly in the deepest layer if the soil is shallow, coarse, vegetated, and lacking snow cover. In the experiments, alpine and Northern regions that were snow covered for part or all of the year spun up slowly or not at all. Soil columns are often assigned 2-m or shallower depths in LSM simulations, which would likely result in spinup times that are shorter than those exhibited here.

The primary meteorological controls on spinup times are freezing temperatures and precipitation. Freezing halts infiltration and redistribution of soil water and encourages the accumulation of snow. In the experiments, humid regions spun up much more quickly than arid regions, and deserts such as the Sahara were very slow to adjust after an overly wet or overly dry initialization. For the reasons outlined in this and the previous paragraph, large-scale simulations that encompass many soil, vegetation, and climate types often will be slower to approach appropriate moisture conditions throughout the domain than smaller-scale, more homogeneous simulations where the range of soil wetness, and thus the difficulty in selecting an initial value, is reduced.

If forcing availability, time, and computer resources are not issues, then allowing a model to integrate through the years (as many as possible) leading up to the start of an experimental period is the best way to initialize a simulation. That is rarely the situation. If multiple years of forcing are available but all or most are within the experimental period, then the following technique is suggested. First, the spinup should start from middling to wet initial states and loop through all available years of forcing until a desired level of equilibrium is attained. Next, the mean state fields for the precise time of year of the start of the experimental period should be computed based on output from the last complete loop. These fields should then be used to initialize the experiment. If it is an issue, computing time can be reduced by performing all or part of the spinup procedure at a low spatial resolution and later interpolating to the desired resolution. These recommendations are based on tests with the Mosaic LSM, but the relative effectiveness of the initialization techniques are likely to apply to other models.

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